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Evaluation Tests of Platinum Resistance Thermometers for a Cryogenic Wind Tunnel Application

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EVALUATION TESTS OF PLATINUM RESISTANCE THERMOMETERS
FOR A CRYOGENIC WIND TUNNEL APPLICATION

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SUMMARY

Thirty-one commercially designed platinum resistance thermometers were evaluated for applicability to stagnation temperature measurements between $-190^{\circ}C$ and $+65^{\circ}C$ in the Langley Research Center's National Transonic Facility. Evaluation tests included x-ray shadowgraphs, calibrations before and after ageing, and time constant measurements. Two wire-wound low thermal mass probes of a conventional design were chosen as most suitable for this cryogenic wind tunnel application.

INTRODUCTION

The stagnation temperature of the Langley Research Center (LaRC) National Transonic Facility (NTF) (ref. 1) must be measured to within $\pm0.3^{\circ}C$ in the range $-190^{\circ}C$ to $+65^{\circ}C$ for accurate Mach number and Reynolds number determination. Fast response is not an explicit requirement but a thermometer with a time constant of less than 10 seconds is desirable in order to verify a stable test condition and to minimize test time. A platinum resistance thermometer (PRT) was selected for this application.

The market was surveyed for a PRT probe that would meet these accuracy and response time requirements. Manufacturers were reluctant to guarantee a $\pm0.3^{\circ}C$ accuracy for repeated temperature measurements, especially for their fast response probes. It was therefore necessary to set up a program to test candidate sensors. The purpose was to find the fastest responding PRT sensor consistent with specifications in accuracy, calibration stability, and mechanical reliability.

Initially, 13 probes and duplicates from 7 manufacturers were purchased for testing. An additional five probes became available later and were included in the test program. The probes were typically wire-wound or thin-film platinum resistance elements cemented to a mandrel 2.5 cm long and surrounded with a metallic sheath. Four-wire leads were specified whenever possible. Each probe was assigned a simple 3-digit identification number. The first digit shows the source and the last digit the number of the probe from that source. A non-zero second digit indicates an additional model in that probe category.

SYMBOLS

R (273.15K)   resistance at the ice point 273.15K, Ω

R_o resistance at the ice point $0^{\circ}C$, Ω

R_t resistance at temperature, t, Ω

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T_{68} absolute temperature on the International Practical Temperature Scale of 1968 (IPTS-68), K (ref. 2)

T_o absolute temperature at the ice point, K

$t = T_{68} - T_o$ temperature, ^oC

$W(T_{68})$ resistance ratio $R(T_{68})/R(273.15K)$

$W_{CCT-68}(T_{68})$ reference resistance ratio adopted by the Comité Consultatif de Thermometrie (CCT) of the Comité International des Poids et Measures (ref. 2)

α, β, δ: constants in the Callendar-Van Dusen equation ($t > 0^oC$, $\beta = 0$)

TESTS AND RESULTS

X-Ray Analysis

An x-ray shadowgraph was made of each probe to provide internal construction details such as positions of lead attachments. This formed a baseline for diagnostics in case of failure and a point of comparison for future procurements of similar PRTs. Typical x-ray shadowgraphs are shown in figure 1.

Calibration

Key to a PRT evaluation is its calibration, i.e., its individual temperature-resistance relationship (ref. 2). The Callendar-Van Dusen equation shows the relationship for platinum to be,

$$\frac{R_t}{R_o} = 1 + \alpha \left[t - \delta(\frac{t}{100})(\frac{t}{100} - 1) - \beta(\frac{t}{100} - 1)(\frac{t}{100})^3 \right]$$

This has been modified for thermometry in the International Practical Temperature Scale of 1968 (IPTS-68) (ref. 3) where the ratio of resistance of a thermometer is expressed as W_{CCT-68}. Below 0^oC (273.15K) in the IPTS-68, probe calibrations are shown as a difference ratio ΔW from a reference ratio such that $W(T_{68}) = W_{CCT-68} + \Delta W(T_{68})$. The problem is how to display the calibration data such that changes are shown in a clear, and meaningful way while minimizing the required number of calibration points. Carr (ref. 4) chose to use α and time variations in α. Corruccini (ref. 5) and Sinclair et al (ref. 6) used a ratio of resistance difference, Cragoe's z functions, defined as,

$$Z_t = (R_t - R_{t1})/(R_{t2} - R_{t1}) \text{ where } t_1 < t < t_2$$

For simplicity the data in the current work was compared with the Callendar-Van Dusen equation with $\alpha = 0.00392$. Equivalent temperature difference is shown rather than the measured resistance after an early attempt to standardize with $R_o = 100 \; \Omega$ proved too restrictive.

Operational probes at NTF are calibrated in accord with IPTS-68 procedures (ref. 2). The PRT evaluation tests conducted were somewhat less stringent. First, all probes were calibrated at the ice point (0^oC) to measure R_o, as a measure of interchangeability. The initial calibration R_o data tabulated in Table I with

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equivalent temperature differences show the degree of interchangeability which may be expected from a cross section of industrial PRT's.

Next, the resistance was measured in boiling liquid nitrogen (nominally at $-195.8^{\circ}C$) for a quick look at the span of the temperature-resistance curve. "Initial" LN_2 point data are also listed in Table I as temperature equivalent differences.

To further investigate the shape of the calibration curve in order to detect, for example, any strain effects in the PRT, additional data points were taken at room temperature ($\sim 20^{\circ}C$), $-40^{\circ}C$, $-80^{\circ}C$ and $-100^{\circ}C$. These are shown in figure 2 for the two probe types later selected for more extensive tests, (series no. 31 and 50). The fastest responding probes, series no. 41 and 42 were rejected at this point because of their extreme sensitivity to strain. The no. 50 probes matched the $\alpha = 0.00392$ curve within $\pm 0.2^{\circ}C$ down to $-100^{\circ}C$ throughout the period of harsh testing. The no. 31 probes showed some instability during calibration. The scatter of $\pm 0.4^{\circ}C$ is apparently characteristic of the probe design rather than deterioration caused by the tests.

The temperature range $-100^{\circ}C$ to $-190^{\circ}C$ is critical to NTF so a special effort was made to detail the temperature-resistance curve in this range. The probes under test are not adaptable to a cryostat for calibration and liquid calibration baths were not available below $-100^{\circ}C$. Therefore, a comparison calibration was attempted with a standard PRT and the candidate PRT each inserted into a thermal equalizer block. In one case, the block (aluminum) was chilled to LN_2 temperature, shrouded with an insulator then allowed to drift back to room temperature. In another test the block was placed in a chamber cooled by expanding nitrogen to a temperature below $-100^{\circ}C$. Neither approach showed the necessary precision because of poor sensor-to-block thermal contact and the need to thermally temper the probe stem.

Pre-Ageing Tests

Prior to ageing the probes, each was tested for self-heating, electrical insulation, and immersion effects.

To test for self-heating, the probes were held horizontally in still air. A milliamp level current was then applied to the appropriate leads across the PRT as the voltage drop was monitored. The current was gradually increased until the resulting internal joule heating began to affect the readings. This test setup is conservative because heat is transferred away from the probe by free convection only. The actual NTF application will involve forced convection with a typical stream velocity of 15 m/sec at pressures up to 9 atmospheres. Probes 50-1 and 50-2 ($R_0 = 1,000 \,\Omega$) showed no self-heating at 0.1 mA dc (equivalent to 100 mV with the sensor at $0^{\circ}C$.) Probes 31-1 and 31-2 ($R_0 = 100 \,\Omega$) were able to take 0.5 mA without self-heating.

Electrical insulation was measured with a 5 volt insulation tester at room and LN_2 temperatures. The resistances were usually 10^3 megohms or greater. Lower values indicated defects in insulation which showed up as intermittent shorts under vibration.

The probes were then immersed into LN_2 to check the immersion depth required to negate heat transfer down the stem and for any thermoelectric voltages which might disturb the electrical resistance measurement. The immersion was done in increments

of 2.5 cm and the resistance of the sensor monitored at each depth until the resistance value stabilized. This depth was then recorded as the minimum working depth. The polarity of the current was reversed during this process to check for thermoelectric effects. As an example of the results, probes 31-1 and 31-2 required a 10-cm immersion and were without thermoelectric effects. Probes 50-1 and 50-2 required an immersion of only 2.5 cm to eliminate stem conduction but indicated thermoelectric voltages equivalent to an error of $\pm 0.1^{\circ}C$ for up to an 18 cm immersion. The 31 and 50 type probes were of interest at this point because of their demonstrated rapid response on immersion into LN_2.

Ageing Tests

The probes were thermally cycled 100 times by inserting the sensor tip into a LN_2 bath long enough for the tip to reach $-190^{\circ}C$ and then returning it to ambient air until it indicated a temperature above $0^{\circ}C$. The setup for the ageing tests is shown in figure 3. The tests were automated with a push-pull cyclic drive mechanism shown in the figure. Dwell time in the LN_2 bath and warm-up time out of the bath were pre-set on the interval timers according to the needs of the probe under test.

Most of the probes physically survived the full 100 cycles and were then recalibrated. Calibrations before and after ageing for probes 31-1, 31-2, 50-1, and 50-2 are plotted in figure 2 as a deviation from the Callendar-Van Dusen equation with $\alpha = 0.00392$. It appears from these data that individual calibrations will be required to meet the accuracy goal of $\pm 0.3^{\circ}C$. Calibration stability appears excellent for probes 50-1 and 50-2. The integrity of the probes selected for the NTF application was partially determined by the stability of the calibration effected by this test.

Time Constant Measurement

The response time of each probe was demonstrated during the immersion and ageing tests. Time constants (time required for the probe to respond to 63% of a temperature change) were found on immersion into liquid nitrogen. These data have limited value because nitrogen nucleation alters the heat transfer and is further influenced by the sensor geometry.

More meaningful time constant measurements were made on some of the probes using a small calibration wind tunnel as a test facility. The tunnel was operated at ambient temperature, one atmosphere pressure and a velocity of 15 meters/sec. This facility and the associated test equipment used is shown in figure 4.

Time constants were determined by two methods. In the first method, the entire probe (sensing element, insulation, and sheath) was heated with a heat gun external to the tunnel, then quickly inserted into the air stream to cool. The time constant is then determined from the exponential decay of temperature with time. This method, however, is not compatible with current cryogenic wind tunnel facilities because the probe is inaccessible and the environment is hostile. Therefore, a method for an in situ measurement was designed.

The second method used the temperature sensitive resistance element as a heat source. An alternating current was superimposed on the element above the direct current used for resistance measurements, to such a level as to cause obvious self-heating. With the probe affixed to the tunnel wall and the sensor in the stream with

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a measurable "self-heating" the ac power was switched off. Time constants were obtained from the exponential return of the sensor temperature to stream temperature. These data are tabulated in Table II.

Comparison of the data show the time constant to be lower with the second method. Further analysis is required to explain the difference. The data served as a basis for the selection of more responsive probes for additional tests. Probes 31-1 and 50-1 were then tested in the 0.3 M Transonic Cryogenic Tunnel (TCT) using the second (internal heat) method. The results show a comparable time constant for the same pressure and velocity at a temperature of -170°C.

Operational Tests

Finally, the two fastest responding probes which matched best the Callendar-Van Dusen platinum temperature-resistance equation without effects of strain and drift were used operationally. Probes 31-1, 31-2, 50-1, and 50-2 are in continuous use in the 0.3 M TCT and are periodically checked to determine any defects or calibration changes which might occur because of actual tunnel conditions. These data are also shown in figure 2.

CONCLUDING REMARKS

Probe type 50 most closely meets the requirements and was chosen as the primary temperature sensor for the NTF application. It was fast in response (with a 10 second time constant), closely matched to the Callendar-Van Dusen equation and had a calibration stability of $\pm 0.2^\circ$C. Probe type 31 with approximately the same time constant but inferior calibration stability ($\pm 0.4^\circ$C) was selected as a backup sensor.

The two fastest responding probe types (41 and 42, both of special design) were rejected for not meeting the accuracy requirement. One had a thermoelectric output equal to errors of up to 3°C until fully immersed in LN_2. The other was not strain free and showed the effect of side loads caused by buffeting air flow. The other probes showed low thermoelectric voltage and strain effects. Probe 20 was reasonably fast but had a weak attachment point on the leads. Most of the remaining probes were marginal in terms of their calibration stability with thermal cycling and match to the Callendar-Van Dusen equation.

Future work will track the history of calibration constants to further evaluate the sensors. Finally, a new generation probe, an adaptation of a laboratory standard PRT will be used along with probe 50 and 31.

References

1. McKinney, L. W. and Gloss, B. B., "Status of the National Transonic Facility," AIAA 82-0604 paper presented at the AIAA 12th Aerodynamic Testing Conference, Williamsburg, VA, March 22-24, 1982.

2. The International Practical Temperature Scale of 1968, Metrologia, International Journal of Scientific Metrology, Vol. 5, No. 2, pp. 35-44, Springer-Verlag, Berlin, April 1969.

3. Riddle, J. L., Furukawa, G. T., and Plumb, H. H., "Platinum Resistance Thermometry," National Bureau of Standards, Monograph 126, April 1973.

4. Carr, K. R., "An Evaluation of Industrial Platinum Resistance Thermometers," Temperature Its Measurement and Control in Science and Industry, Vol. 4, Part 2, p. 971-982, (Reinhold, 1971).

5. Corruccini, R. J., "Interpolation of Platinum Resistance Thermometers, 10° to $273.15^{\circ}K$," Temperature Its Measurements and Control in Science and Industry, Vol. 3, Part 1, p. 329-338, (Reinhold, 1962).

6. Sinclair, D. H., Terbeek, H. G., and Malone, J. H., "Calibration of Platinum Resistance Thermometers," Temperature Its Measurement and Control in Science and Industry, Vol. 4, Part 2, p. 983-988, (Reinhold, 1971).

TABLE I.- INITIAL CALIBRATION DATA

Probe Number	Resistance R_0 Ω	Ice Point Temperature Equivalent Difference $^{\circ}C$	LN_2 Point Temperature Equivalent Difference $^{\circ}C$
10-1	99.975	-.06	+.52
10-2	99.966	-.09	+.55
20-1	100.032	+.08	+.58
20-2	Note 1	--	--
30-1	99.994	-.02	+.59
30-2	100.002	+.01	+.61
31-1	99.892	+.27	+.52
31-2	100.059	+.15	+.55
40-1	99.981	-.05	+.48
40-2	100.026	+.07	+.56
41-1	99.926	-.18	+.25
41-2	100.018	+.05	+.59
42-1	99.468	-1.34	+.37
42-2	100.136	+.34	+.43
50-1	1000.18	+.04	+.38
50-2	1000.30	+.08	+.36
51-1	99.885	-.29	+.45
51-2	99.910	-.26	+.22
51-3	99.863	-.34	+.03
52-1	500.09	+.05	+.39
52-2	499.91	-.05	+.34
52-3	500.10	+.05	+.42
52-4	500.12	+.06	+.38
60-1	99.84	-.40	+.56
60-2	99.82	-.45	+.56
61-1	99.69	-.78	+.67
61-2	99.76	-.60	+.73
61-3	99.73	-.68	+.63
62-1	100.046	+.12	--
70-1	100.03	+.07	+2.74
70-2	99.925	-.19	+3.20

Note 1 - Leads broke during initial calibration.

TABLE II.- TIME CONSTANT DATA

Probe Number	Method I (External Heat)	Method II (Internal Heat)
10-1	43 sec.	31 sec.
20-1	11 sec.	7.5 sec.
30-1	13 sec.	9.3 sec.
31-1	9.3 sec.	4.8 sec.
40-1	56 sec.	15 sec.
41-1	5 sec.	1.7 sec.
42-1	1.8 sec.	1.4 sec.
50-1	10.2 sec.	7.3 sec.
61-1	24 sec.	11 sec.

SENSING ELEMENT

SENSING ELEMENT
ENLARGEMENT
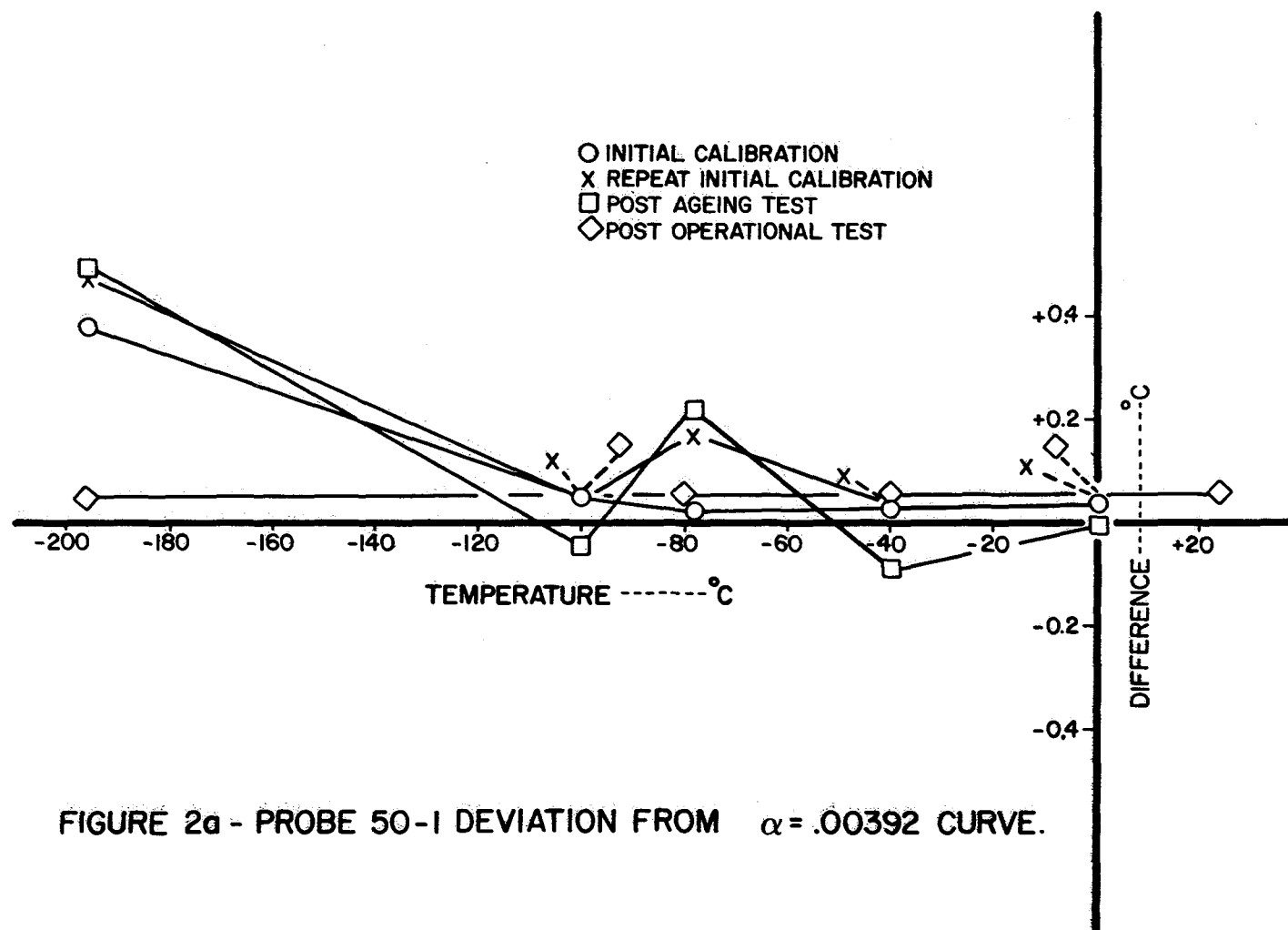
PRT STAINLESS
SHEATH

LEAD ATTACHMENT

Figure 1 - Typical X-Ray Shadowgraph

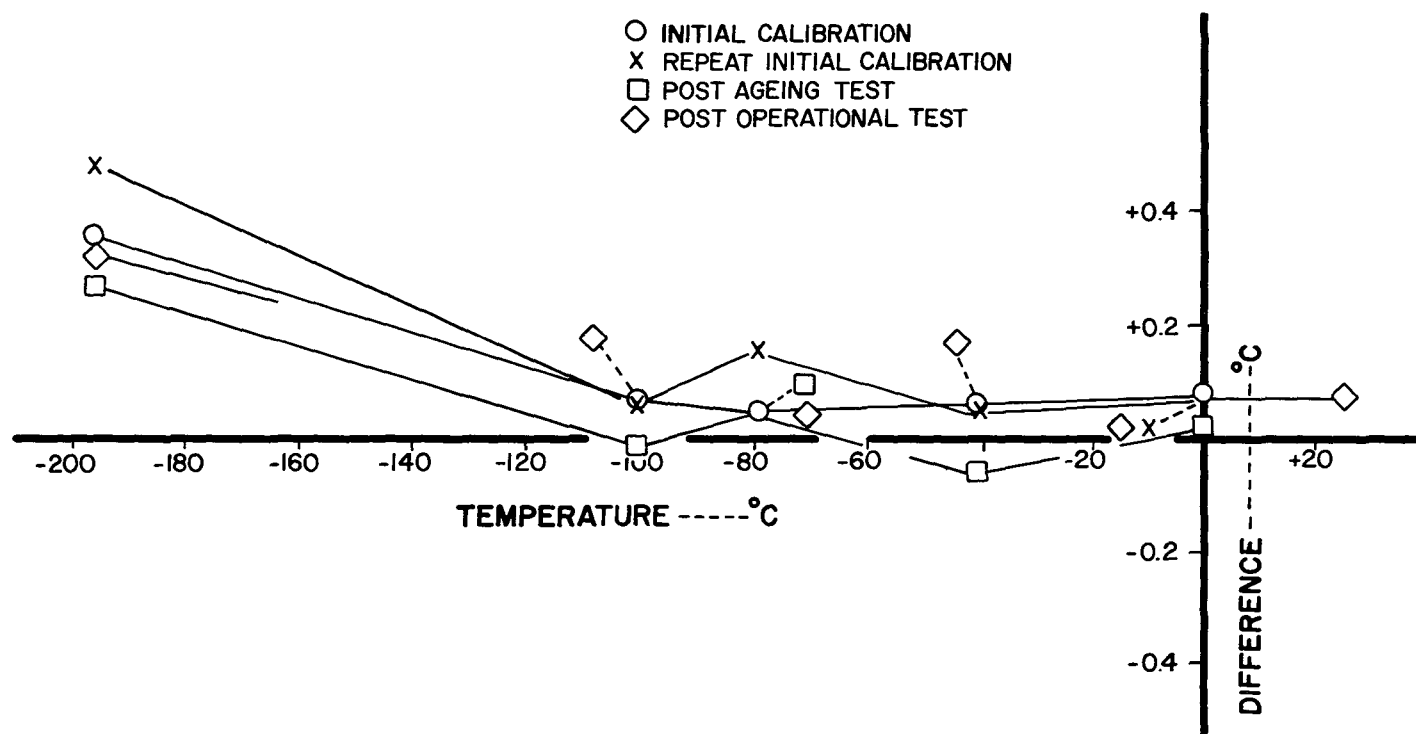FIGURE 2a - PROBE 50-1 DEVIATION FROM α = .00392 CURVE.

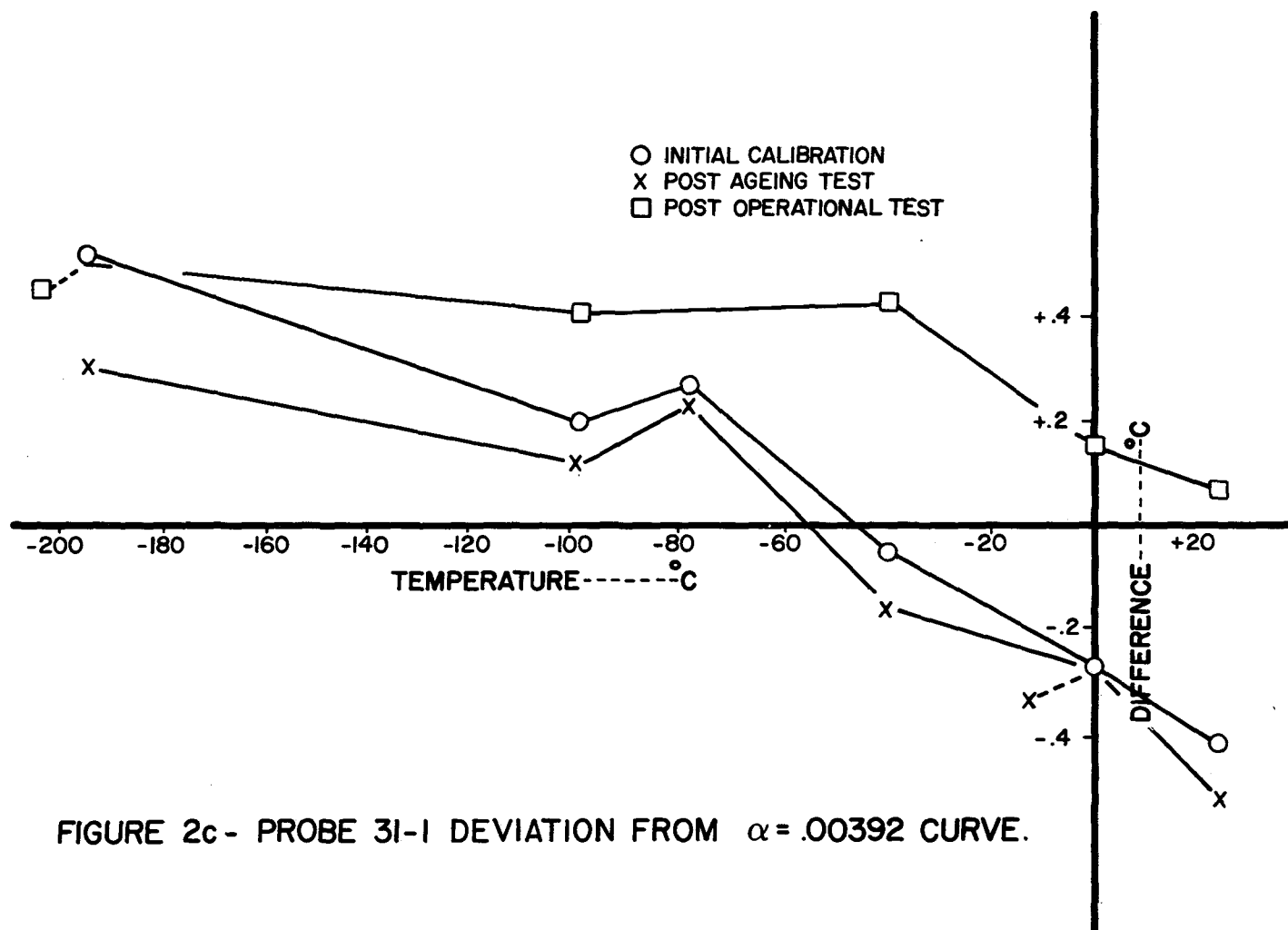FIGURE 2b-PROBE 50-2 DEVIATION FROM α = .00392 CURVE

O INITIAL CALIBRATION
X POST AGEING TEST
□ POST OPERATIONAL TEST

FIGURE 2c - PROBE 3I-I DEVIATION FROM $\alpha = .00392$ CURVE.
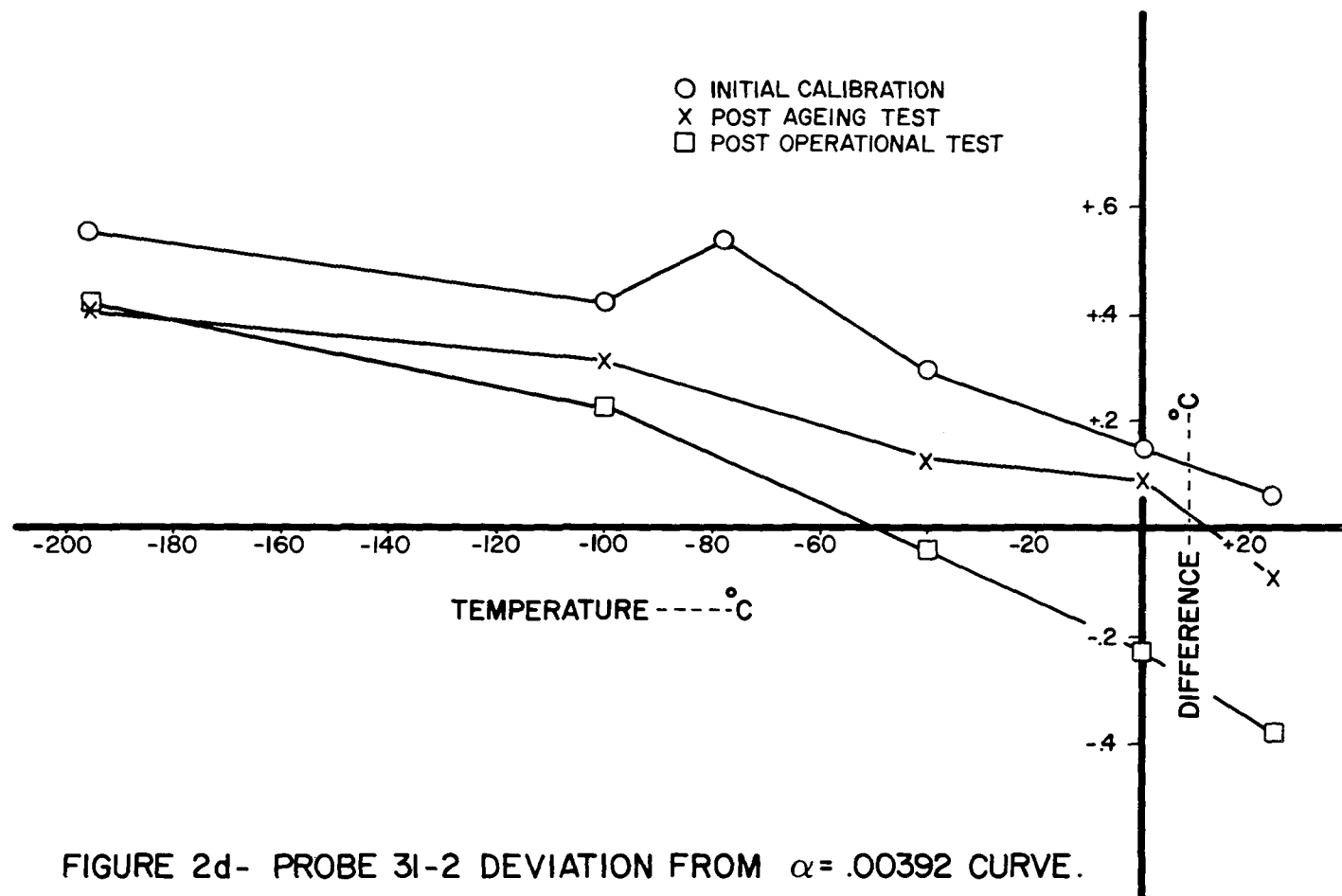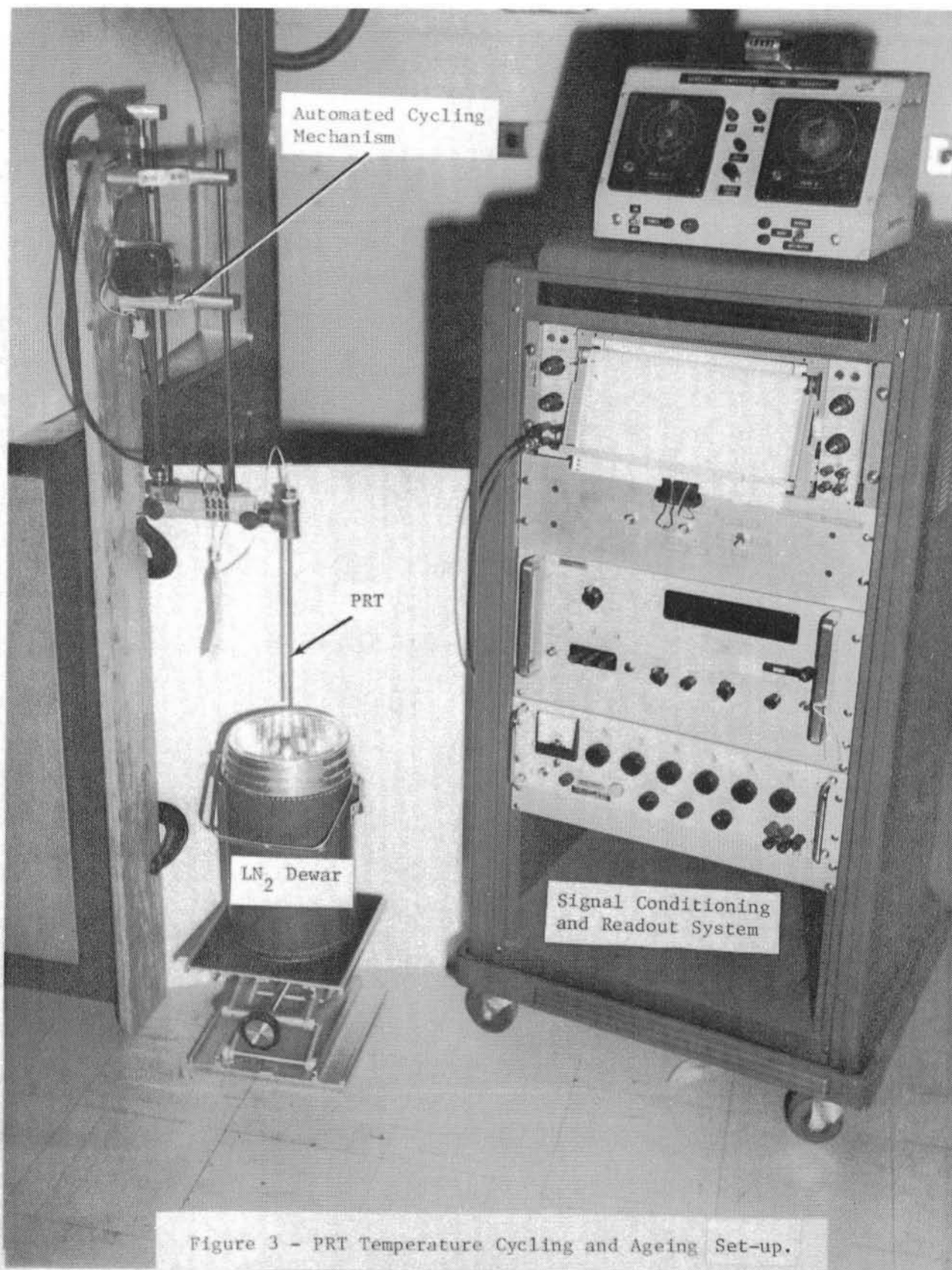
O INITIAL CALIBRATION
X POST AGEING TEST
□ POST OPERATIONAL TEST

FIGURE 2d- PROBE 31-2 DEVIATION FROM α = .00392 CURVE.

Figure 3 - PRT Temperature Cycling and Ageing Set-up.

Wind Tunnel

Test Section

External Heat Source

PRT

PRT Injection Mechanism

Signal Conditioning and Readout System

Figure 4 - Tunnel Test Set-Up.

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15. Supplementary Notes

16. Abstract

Thirty-one commercially designed platinum resistance thermometers were evaluated for applicability to stagnation temperature measurements between $-190^\circ C$ and $+65^\circ C$ in the Langley Research Center's National Transonic Facility. Evaluation tests included x-ray shadowgraphs, calibrations before and after aging, and time constant measurements. Two wire-wound low thermal mass probes of a conventional design were chosen as most suitable for this cryogenic wind tunnel application.

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